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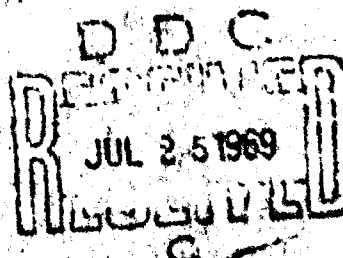
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INSTRUMENTATION OF AN RB-57F TO MEASURE
HIGH ALTITUDE TURBULENCE ENCOUNTERS

by

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SUMMARY

The National Aeronautical Establishment has installed a turbulence instrumentation package and memory recorder on a USAF RB-57F weather reconnaissance aircraft at Kirtland Air Force Base, New Mexico. The object of the project, named "Coldscan", is to record turbulence encounters and temperature changes on routine weather patrol and training flights at altitudes above 50,000 feet. A description of the instrumentation system and its operation is presented along with example data from two of the first project flights. These initial results are most significant for the magnitudes of the temperature gradients encountered near 60,000 feet.

TABLE OF CONTENTS

	Page
SUMMARY	(ii)
1.0 INTRODUCTION	1
2.0 DESCRIPTION OF THE INSTRUMENTATION SYSTEM	1
2.1 The NAE Memory Recorder	1
2.2 Transducers	2
2.3 Signal Conditioning and Recorder Control	2
2.4 Digital Time Clock	2
3.0 GEOGRAPHICAL POSITION AND THE NAVIGATOR'S LOG	3
4.0 PROJECT FLIGHTS	3
5.0 FLIGHT DATA	3
5.1 Flight #2, January 31, 1969	3
5.2 Flight #3, February 3, 1969	4
6.0 CONCLUSIONS	5
7.0 ACKNOWLEDGEMENT	5

TABLES

Table	Page
1 Coldscan Measurement Parameters	6
2 Exceedance Levels	7
3 Navigator's Data Log - Flight #2	8

ILLUSTRATIONS

Figure	Page
1 The RB-57F	9
2 Functional Block Diagram of Coldscan Instrumentation	10
3 Memory Recorder	11
4 Signal Conditioner	12
5 Power Supply and Attitude Gyro	13

ILLUSTRATIONS (Cont'd)

Figure		Page
6	Control Panel	14
7	NAE Time Clock	15
8	Flight #2 Data, Jan. 31, 1969	16
9	Flight #3 Data, Feb. 3, 1969	17
10	Flight Routes and Event Positions	18
11	Computed Gusts for Event 1 of Flight #3	19

INSTRUMENTATION OF AN RB-57F TO MEASURE HIGH-ALTITUDE TURBULENCE ENCOUNTERS

1.0 INTRODUCTION

A considerable amount of atmospheric turbulence data has been reported in recent years for aircraft flying in the troposphere. Studies have included the detailed measurement of turbulence by specially instrumented military-type aircraft, as well as the recording of turbulence encounters on routine flights by commercial transport aircraft. The British Civil Aircraft Airworthiness Data Recording Programme and the NASA VGH data, for example, have produced much valuable information on the operation of civil aircraft on routes all over the world. However, since aircraft are now being constructed to fly at altitudes in excess of 40,000 feet, there is a need to accumulate information on atmospheric conditions at these altitudes. Few aircraft at present operate routinely above 40,000 feet, the RB-57F of the USAF Air Weather Service being a notable exception (Fig. 1).

In a co-operative program labelled "Coldscan", the NAE has recently installed a turbulence instrumentation package and a memory recorder on a USAF RB-57F of the 58th Weather Reconnaissance Squadron, Kirtland Air Force Base, New Mexico. The aims of the project are to study each encounter with high-altitude turbulence with regard to future civil aircraft operations, to relate the nature and severity of the turbulence to geographical position and meteorological conditions, and to investigate the correlation between turbulence and horizontal temperature gradients.

This report will describe the recorder and instrumentation, outline their flight operation, and serve as a reference for future reports that present the results of this investigation. Example data from two of the first project flights will be presented and discussed.

2.0 DESCRIPTION OF THE INSTRUMENTATION SYSTEM

The instrumentation system has been designed to fulfill the measurement, analysis, and operational requirements of the Coldscan program. It is an automated system, continually scanning the data and recording only when significant parameter changes have occurred. The basic system, as shown in Figure 2, includes the transducers, a signal conditioning unit, logic modules, an in-flight calibrator, a digital time clock, a recorder control unit, and a seven-channel FM magnetic tape memory recorder.

2.1 The NAE Memory Recorder

The disadvantage of most airborne systems that record turbulence encounters on routine flights is that they record continuously, so that hours of flight data must be scanned to reveal a single incident. The NAE memory recorder overcomes this disadvantage by virtue of its "memory storage" capability. The recorder has two tapes, a loop with a two-minute period and a reel for permanent record (Fig. 3). The monitored parameters are continuously recorded on the tape loop and are simultaneously scanned by the exceedance detectors for parameter fluctuations exceeding preset values. If an exceedance does occur, the control logics actuate the tape reels for the data transfer from the loop to the storage tape. The two minutes of recorded data prior to the

exceedance are retained, along with the exceedance as long as it persists, plus the two minutes of data following the incident. The supply reel contains approximately five hours of tape, so that as many as 75 incidents can be recorded on each storage reel.

2.2 Transducers

Parameters that are measured for the Coldscan program are shown in Table 1. Along with each parameter is listed the type of transducer, its location on the aircraft, and the recorded range of each variable.

2.3 Signal Conditioning and Recorder Control

The signals from the transducers are fed into the signal conditioner where demodulation, amplification, and filtering are carried out as necessary (Fig. 4).

As the aircraft climbs through 40,000 feet, the altitude exceedance detector turns the loop on automatically and arms the reel to reel drive. The data on the loop will be transferred to the reel tape whenever one or more of the following parameters exceed a preset level (Table 2):

- (i) level of normal acceleration;
- (ii) rate of change of indicated airspeed;
- (iii) rate of change of total temperature.

The reel is activated for approximately four minutes. At any time during the four-minute period, the control logics may be reset by a further exceedance. During the sequence, the information from the loop is transferred to the memory reel as follows:

- (i) the two minutes preceding the incident;
- (ii) a time code superimposed on the altitude-coarse signal eight seconds after the incident;
- (iii) the exceedance and, one minute later, a calibration sequence lasting two seconds;
- (iv) the final two minutes of succeeding data.

Both the loop and the reel drive can also be controlled manually by the control unit located in the navigator's left-hand console (Fig. 6). When selected manual, the loop will remain on indefinitely. The reel switch, although spring-loaded in the "auto-mode" position, can be manually initiated to make a permanent record of any occurrence judged significant by the navigator, but which did not activate the reel automatically.

2.4 Digital Time Clock

Figure 7 shows the NAE-ME digital clock that has been installed in the left console of the navigator's station. The function of the clock is to provide a time reference for correlating geographical position and meteorological conditions with turbulence encounters.

The clock has five registers, capable of counting to 99999 minutes, or about 70 days. It is operated from batteries that are charged when aircraft power is applied to the system. The time is displayed digitally to the navigator and is automatically recorded on the coarse altitude trace at the beginning of each incident. A push-button

is provided on the face of the clock for event-marking of each incident by the navigator.

3.0 GEOGRAPHICAL POSITION AND THE NAVIGATOR'S LOG

Because this instrumentation is carried on routine flights during which other experiments and training are done, the system was designed to be almost completely automatic, depending on the navigator for monitoring, comments, and, most important, navigational data accurate to within three miles. Each time an exceedance occurs, the amber reel light on the control panel indicates to the navigator that a permanent record of the incident is being recorded. The navigator then completes the data log (Table 3) for this event and writes the digital clock time, not only in the log, but also on the route map at the position of the incident. The digital clock time therefore serves as the identifying link between each tape-recorded turbulence encounter and the navigator's computed geographical position and observations. By also marking the clock time on the route map at major course changes, the navigator ensures that geographical positions can be interpolated on tape playback for any incidents that escaped his notice.

4.0 PROJECT FLIGHTS

It is expected that the RB-57F with the NAE turbulence instrumentation and memory recorder will average about two flights a week, mostly on routine operational and training missions at cruising altitudes from 50,000 to above 60,000 feet. Durations of the flights will vary from two to seven hours with an anticipated average of five hours. With the present exceedance levels in the recorder control logics, tapes will likely only have to be changed about once a month.

5.0 FLIGHT DATA

Traces from two of the first Coldscan project flights (#2 and 3) are presented in Figures 8 and 9. The advantage to data analysis of the memory recorder concept is apparent from these two Figures, as all of the incidents that occurred during seven and one-half hours of flight are represented by only 41 minutes of tape. A discussion of the data from each of these flights follows.

5.1 Flight #2, January 31, 1969

Flight #2 was a four-hour and 20-minute flight over New Mexico at altitudes exceeding 60,000 feet. Six exceedances were recorded at the geographical positions labelled 2-1 to 2-6 on the route map of Figure 10. The information from the navigator's data log for this flight appears in Table 3. Note that the navigator has recorded the last incident on his data sheets as events 5 and 6, although the traces indicate that it was one continuous incident, which will be referred to below as event 5/6. During this flight altitude-fine was unserviceable and therefore is not presented in Figure 8. Superimposed on the altitude-coarse trace are the compressed time codes and event marks as well as the calibration pulses that appear on all traces during each event. The bottom trace represents static temperature computed from the altitude, total temperature, and air-speed signals.

Events 2 and 5/6 are significantly longer than the others, indicating that after

the initial exceedance, there were further exceedances to reset the control logics. In all five cases, the storage reel was activated by an exceedance of rate of change of total temperature. Events 1, 3, and 4 are otherwise fairly smooth, whereas Events 2 and 5/6 are definitely associated with turbulence. Near the end of Event 5/6, the turbulence encountered produced $\pm \frac{1}{2}$ g acceleration and ± 10 knot airspeed excursions, during which the pilot reported that the turbulence was moderate.

A most interesting feature of this flight was that Events 2 and 5/6, those with the greatest temperature changes and turbulence, both occurred over the same geographical position two hours apart. The recorder reel was activated in each case by a positive temperature change just on the west side of the Sangre De Cristo Mountains and continued to operate in turbulence for over eight minutes until the aircraft was well south-east of the range. Doppler winds at the flight altitude were from 250 degrees at 45 to 50 knots in each case. The 300 m.b. weather charts for the day of the flight show that a 140-knot jet stream from 240 degrees lay over Albuquerque four hours before take-off. During the flight the jet core moved southward, maintaining its direction, but strengthening to 160 knots, so that three hours after the flight it lay across the south-east corner of New Mexico.

The most important observation from this flight was that the magnitude of the horizontal temperature gradients above 60,000 feet considerably exceeded expectations. Event 2, for example, reveals a static temperature change as great as 15°C in three minutes and another, near the end of the record, of 7°C in 15 seconds. There is evidence that the long wave-length temperature changes of Events 2 and 5/6 are the result of mountain waves, with the moderate turbulence of the last event occurring in a trough of the wave.

5.2 Flight #3, February 3, 1969

In the three-hour and 10-minute flight #3 there were only two exceedances, both over the mountains of northern Colorado, with only two and one-half minutes between them.

In the first of these incidents, the aircraft underwent a small 0.1 g upward and downward acceleration before pitching up five degrees and climbing 900 feet in 10 seconds. It then experienced a series of pitches for the next two minutes and was returned to its original altitude of 63,000 feet. The recorder was activated by an 8°C temperature drop during the initial climb and then reset, probably by both a 0.35 g acceleration exceedance and a following temperature decrease of 12°C in 50 seconds.

The second event reveals a temperature drop of 9°C in 30 seconds, followed by aircraft pitching and 0.35 g exceedances. There is considerably more choppy turbulence evident in this incident than in Event 1 of this flight.

A more detailed analysis of the aircraft response during Event 1 was made to determine if this incident was a result of turbulence or pilot-autopilot input. The results in Figure 11 show load factor, pitch attitude, altitude change, and computed vertical gust velocity for 40 seconds at the beginning of the event. Assuming motion in the vertical plane only, and a linear C_L versus α curve, the vertical gust velocity was computed from the equation

$$w_g = U \left[\frac{(n - 1) W}{qS C_{l_\alpha}} \right] - U(\theta - \theta_0) + g \int_0^t (n - 1) dt$$

where U = true airspeed, assumed constant
 n = load factor in g's
 W = aircraft weight, lb
 q = dynamic pressure, psf
 S = gross wing area
 C_{l_α} = lift-curve slope of the aircraft
 θ = pitch attitude
 g = acceleration of gravity
 w_g = gust velocity, positive upwards.

The calculations show that the aircraft encountered an up and then a down gust, each with peak magnitude of slightly over 20 ft/sec and a duration of about 15 seconds. The 20 ft/sec vertical gust only partially accounts for the average 75 ft/sec rate of climb, the major part being a result of the pitch-up. It can be concluded that some turbulence and wave activity were present and may have contributed to pilot or autopilot input that produced the 900-foot increase in altitude.

6.0 CONCLUSIONS

The NAE memory recorder turbulence package installed on an RB-57F has successfully detected and recorded several high-altitude turbulence and temperature change incidents, and clearly demonstrated its applicability to this type of program. For the flights reported, the most significant feature is the magnitude of the horizontal temperature gradients encountered at altitudes above 60,000 feet. Of the seven events recorded in these two flights, all were associated with temperature change, and in four of them turbulence was experienced.

The program will now continue with the recording of turbulence and temperature change incidents on routine flights, probably at a rate of two flights per week.

7.0 ACKNOWLEDGEMENT

Grateful acknowledgement is given to Mr. Donald Elmore of General Dynamics and to the personnel of the 58th Weather Reconnaissance Squadron, Kirtland AFB, for their assistance in the installation of the NAE instrumentation and the operation of program Coldscan.

TABLE 1
COLDSCAN MEASUREMENT PARAMETERS

Parameter	Transducer	Recorded Range	Location
Normal Acceleration	Linear Servo Accelerometer	$\pm 1.5 \text{ g}$	Upper pressurized electronics bay
Roll Attitude	Vertical Gyro	$\pm 30^\circ$	Upper pressurized electronics bay
Pitch Attitude	Vertical Gyro	$\pm 15^\circ$	Upper pressurized electronics bay
Total Temperature	Unheated Fast-Response Total Temperature Probe	$-40^\circ\text{C} \pm 14^\circ\text{C}$	Aircraft nose
Altitude Coarse	Force Balanced Altitude Pressure Transducer	50,000 ft $\pm 20,000 \text{ ft}$	Pilot's station - under seat
Altitude Fine	Force Balanced Altitude Pressure Transducer	4,000 ft steps	Pilot's station - under seat
Indicated Airspeed	Force Balanced Indicated Airspeed Transducer	140 knots $+ 40 \text{ knots}$	Pilot's station - under seat
Time	NAE-ME Digital Time Clock	0 to 99999 minutes	Navigator's station - left console

TABLE 2

EXCEEDANCE LEVELS

Parameter	Exceedance Level	State of Memory Recorder
Altitude - C	40,000 ft	Loop Drive Activated Reel Armed
Total Temperature - LO	5°C/min	Reel Activated
Total Temperature - HI	1.25°C/sec	Reel Activated
Indicated Airspeed	5 knots/sec	Reel Activated
Normal Acceleration	0.35 g	Reel Activated

TABLE 3

NAVIGATOR'S DATA LOG - FLIGHT #2

TAKE-OFF:	Digital Clock	1828	Digital Clock	2106
	GMT	1652	GMT	2113
	Weight	59800	Weight	45300
			LANDING:	

Event No.	Digital Clock Time (Min)	GMT	Weight (Lb)	Winds Deg/Kts	Altitude Ft (1000's)	Navigator's Comments
1	1907	1809	54200	265/75	61.8	In turn - Clear weather - No rapid change in temp.
2	1912	1814	54000	250/75	62.2	Light turbulence - Clear weather
3	1937	1834	53100	Unable	61.1	In turn - No turbulence
4	1956	1853	52000	260/35	62.6	No turbulence - Clear 4 to 5° temp. change
5	2046	2013	48200	250/45	63.8	Light chop - 5° temp. change - Altitude ± 500 ft
6	2049	2016	48200	257/82 (?)	63.5	Moderate turbulence 5° temp. change - Altitude ± 1000 ft



FIG. 1: THE RB-57F

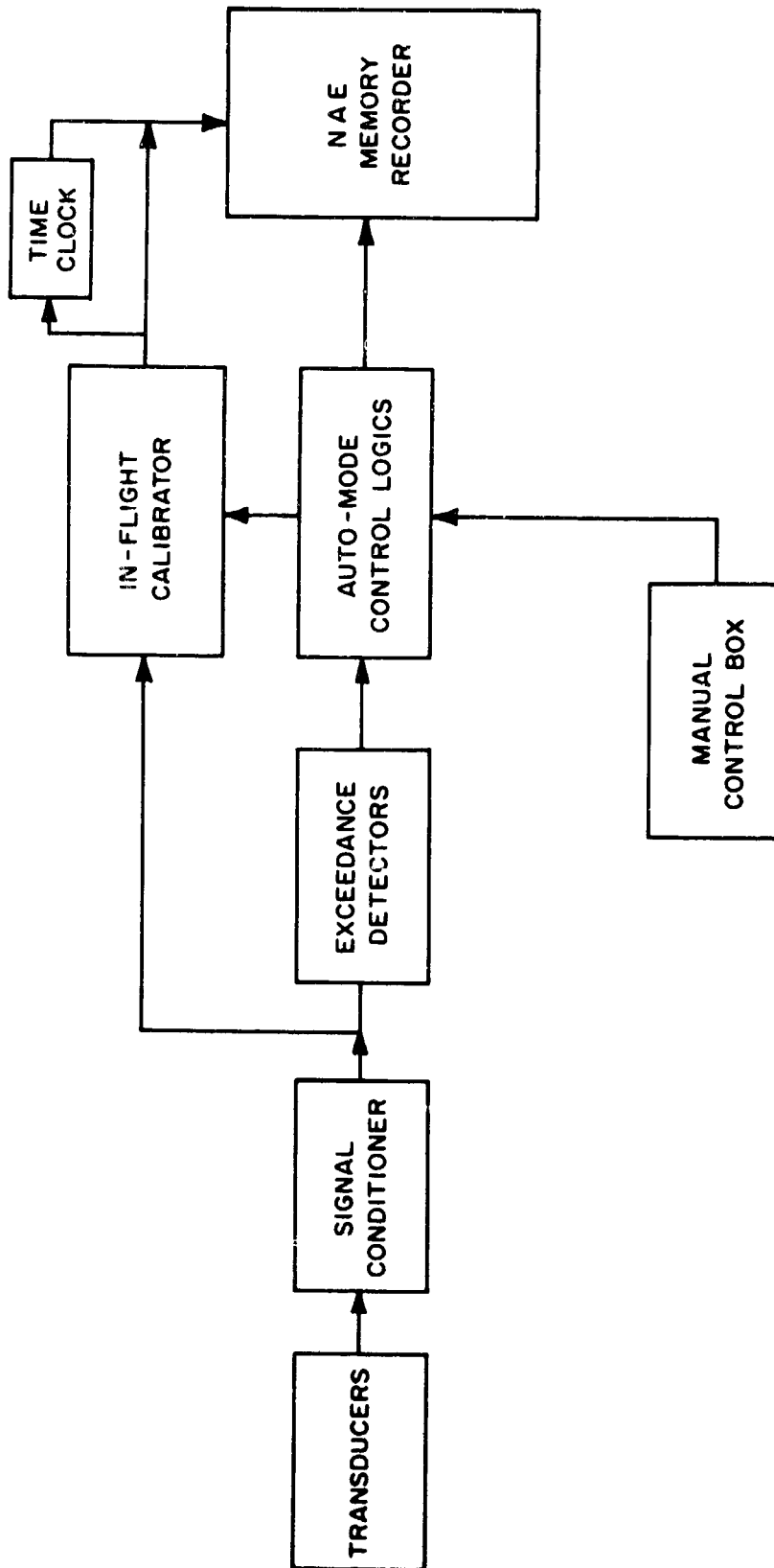


FIG. 2: FUNCTIONAL BLOCK DIAGRAM OF COLDSCAN INSTRUMENTATION

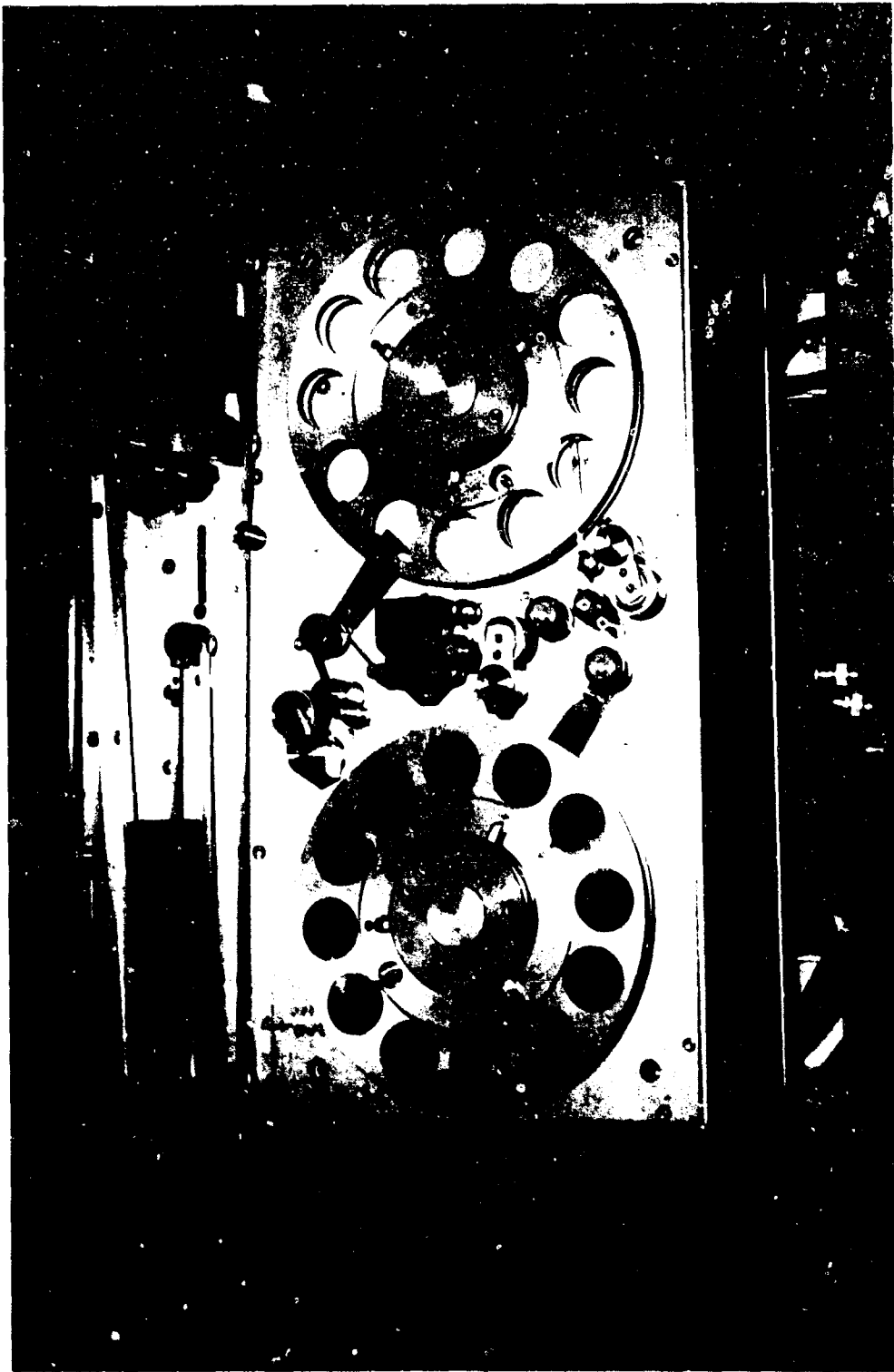


FIG. 3: MEMORY RECORDER

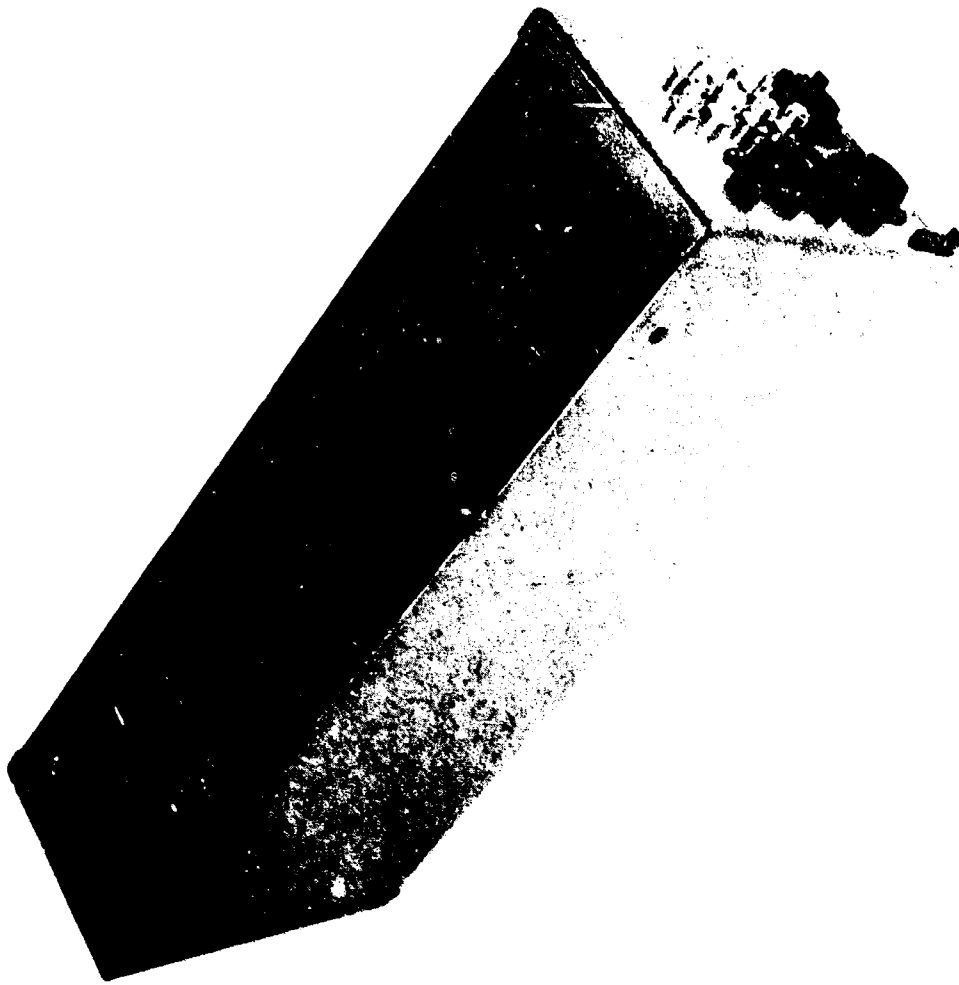


FIG. 4: SIGNAL CONDITIONER

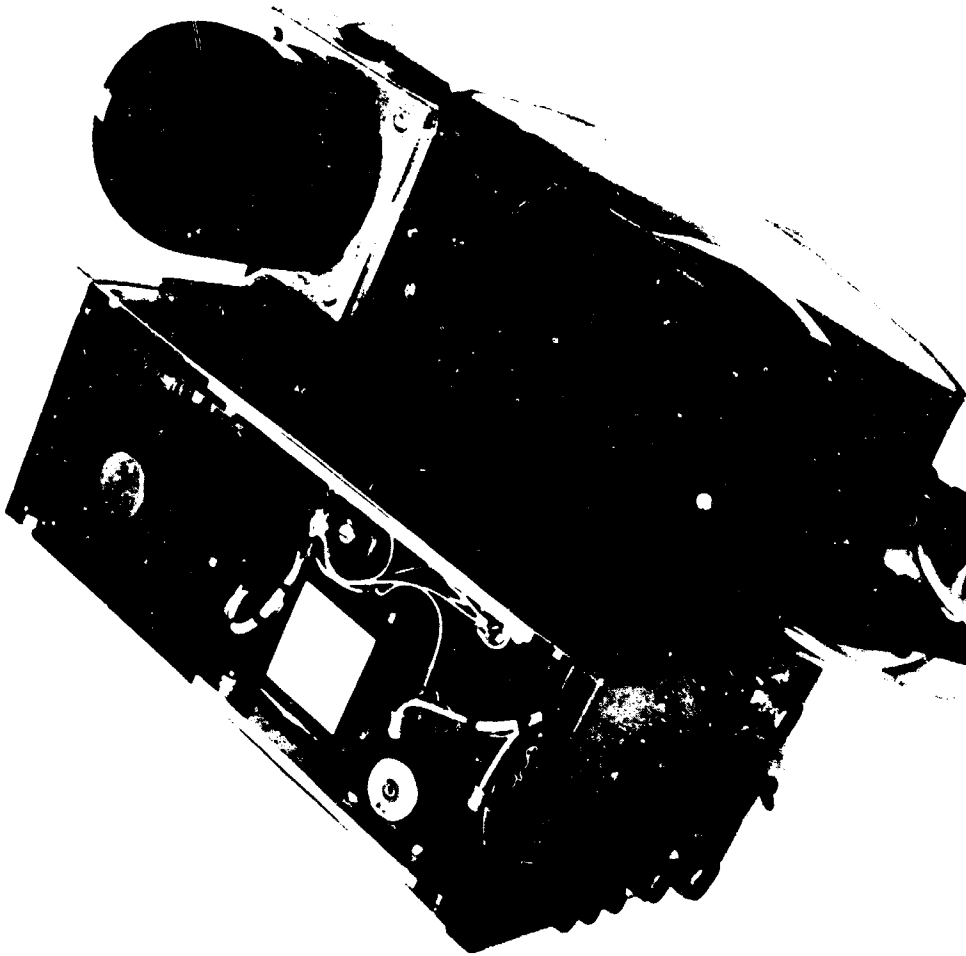


FIG. 5: POWER SUPPLY AND ATTITUDE GYRO

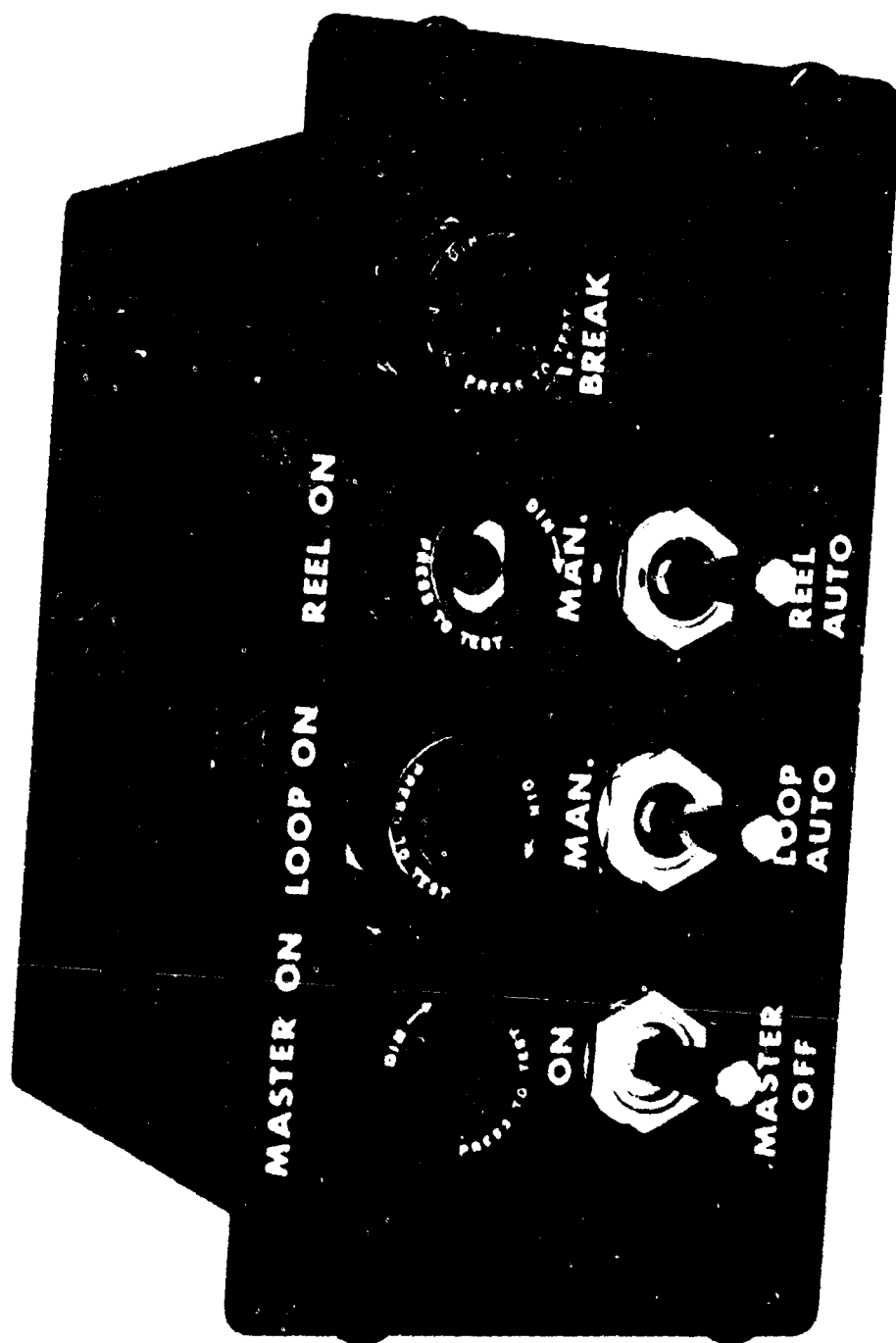


FIG. 6: CONTROL PANEL

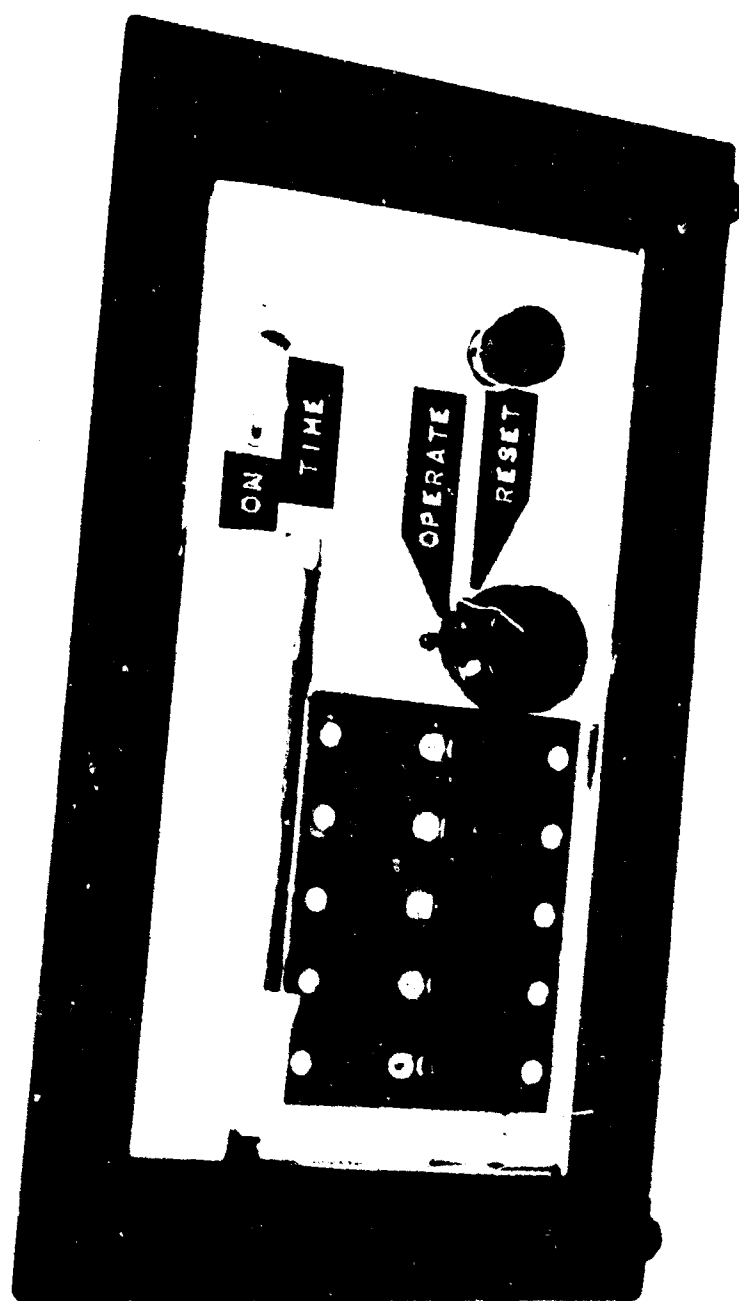


FIG. 7: NAE TIME CLOCK

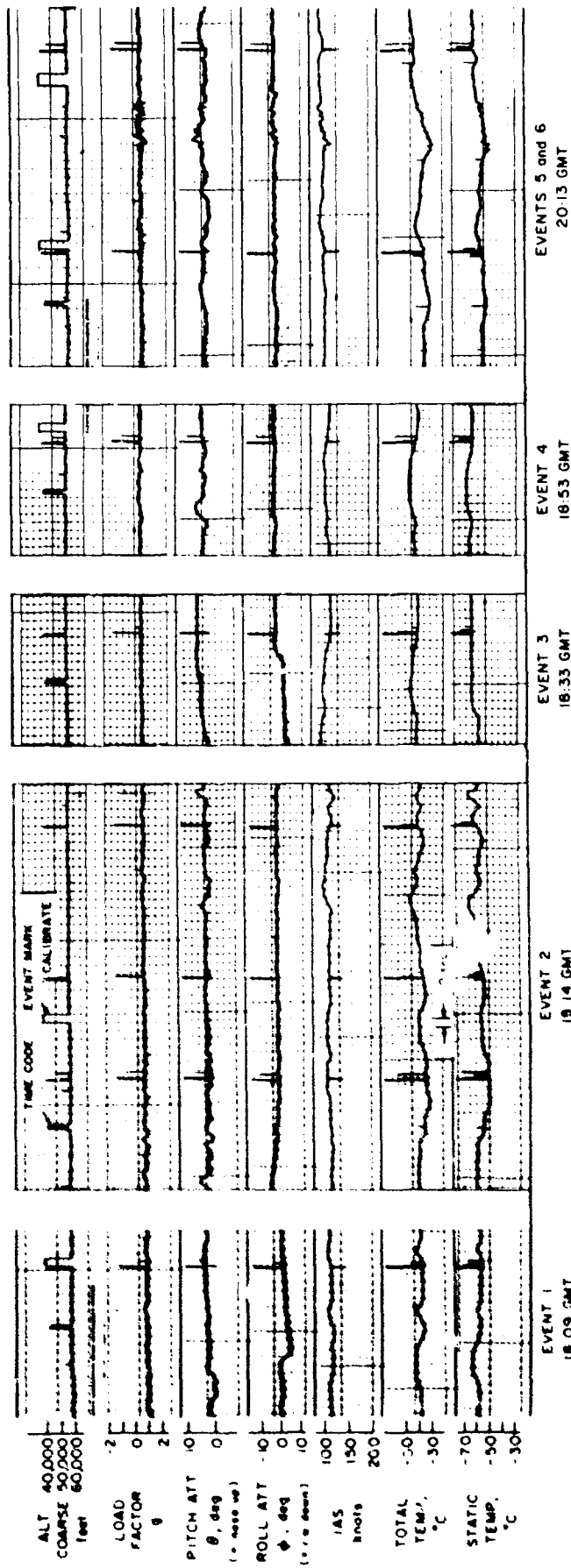


FIG. 8: FLIGHT #2 DATA, JAN. 31, 1969

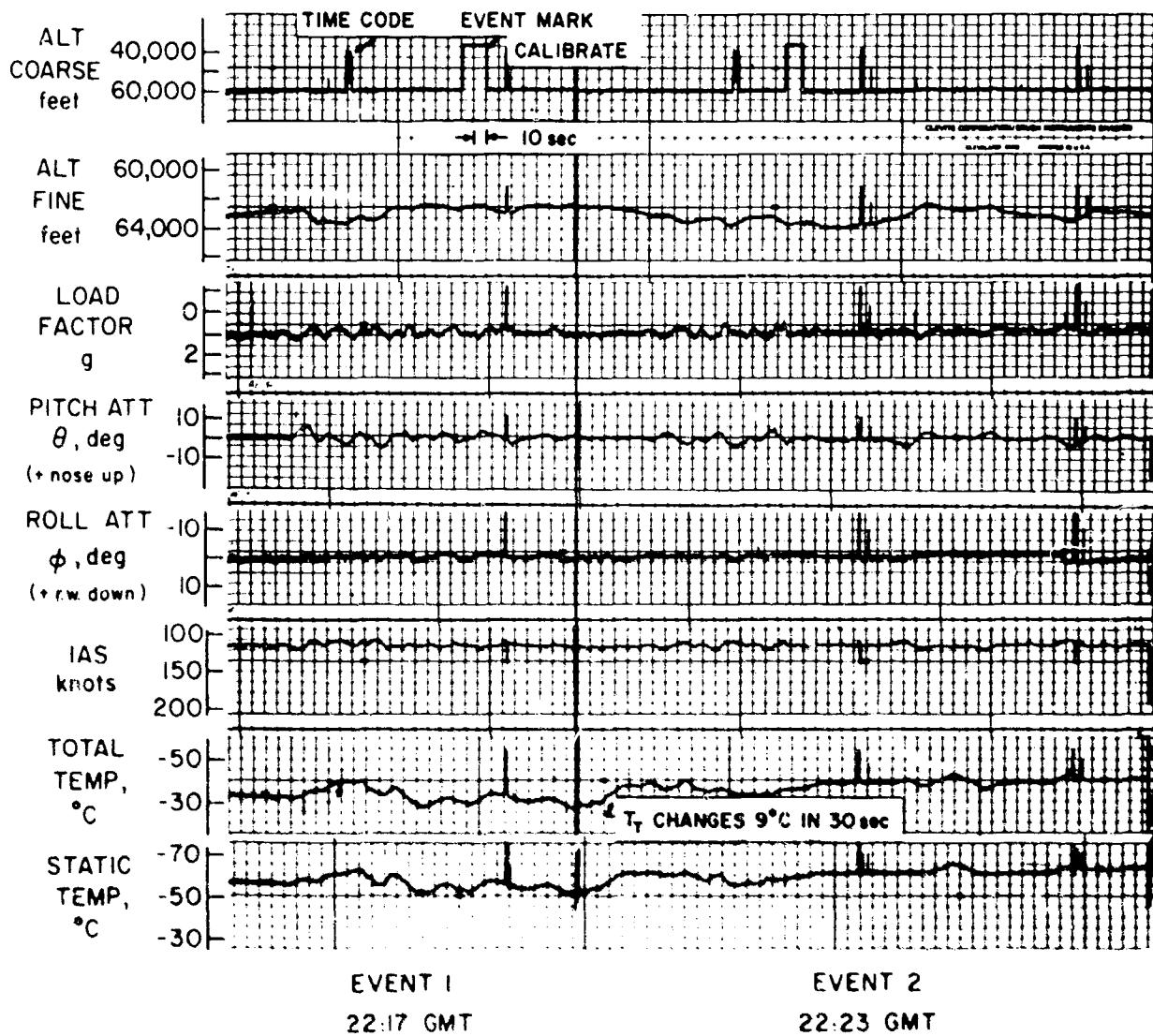


FIG. 9: FLIGHT #3 DATA, FEB. 3, 1969

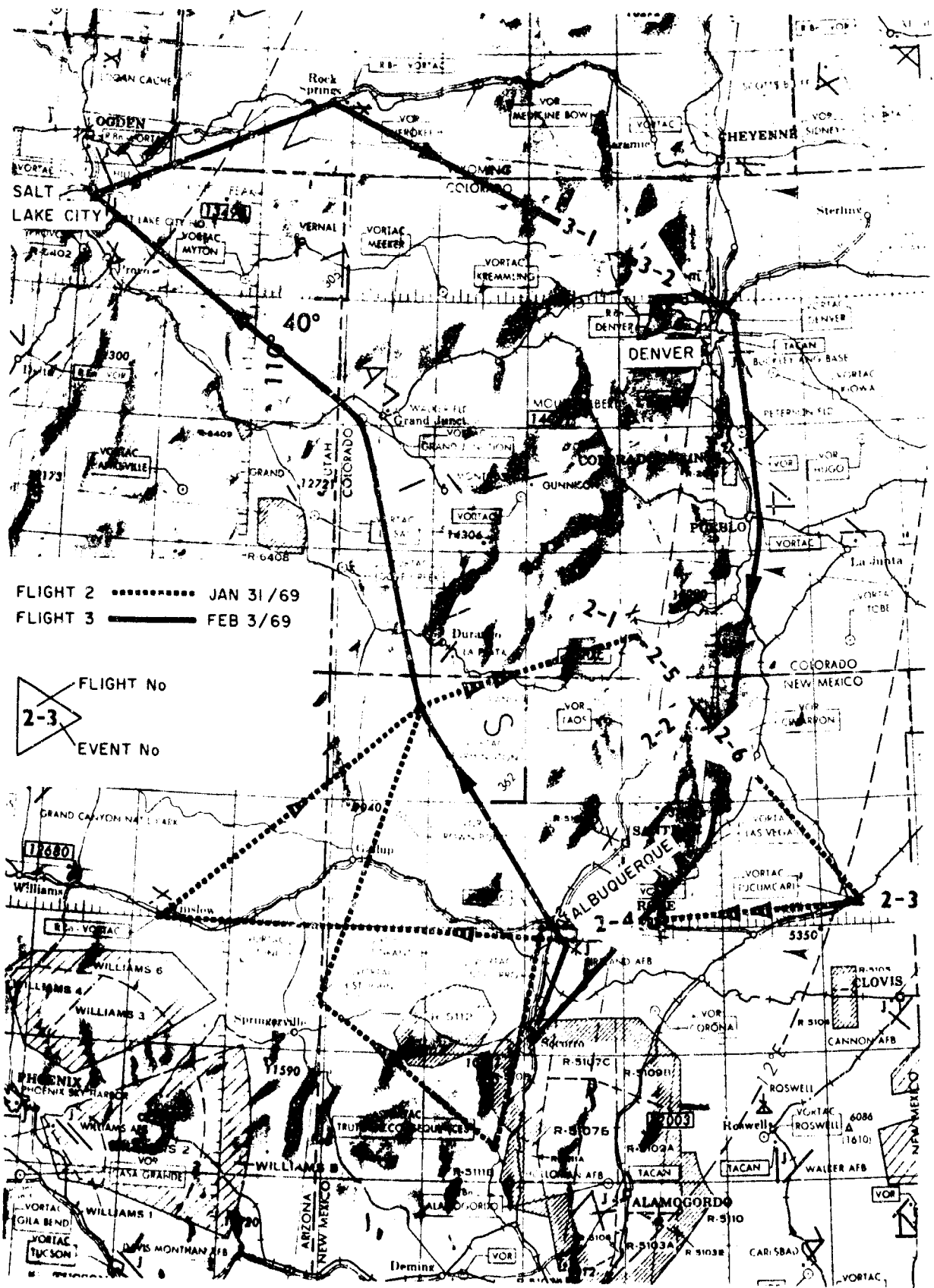


FIG. 10: FLIGHT ROUTES AND EVENT POSITIONS

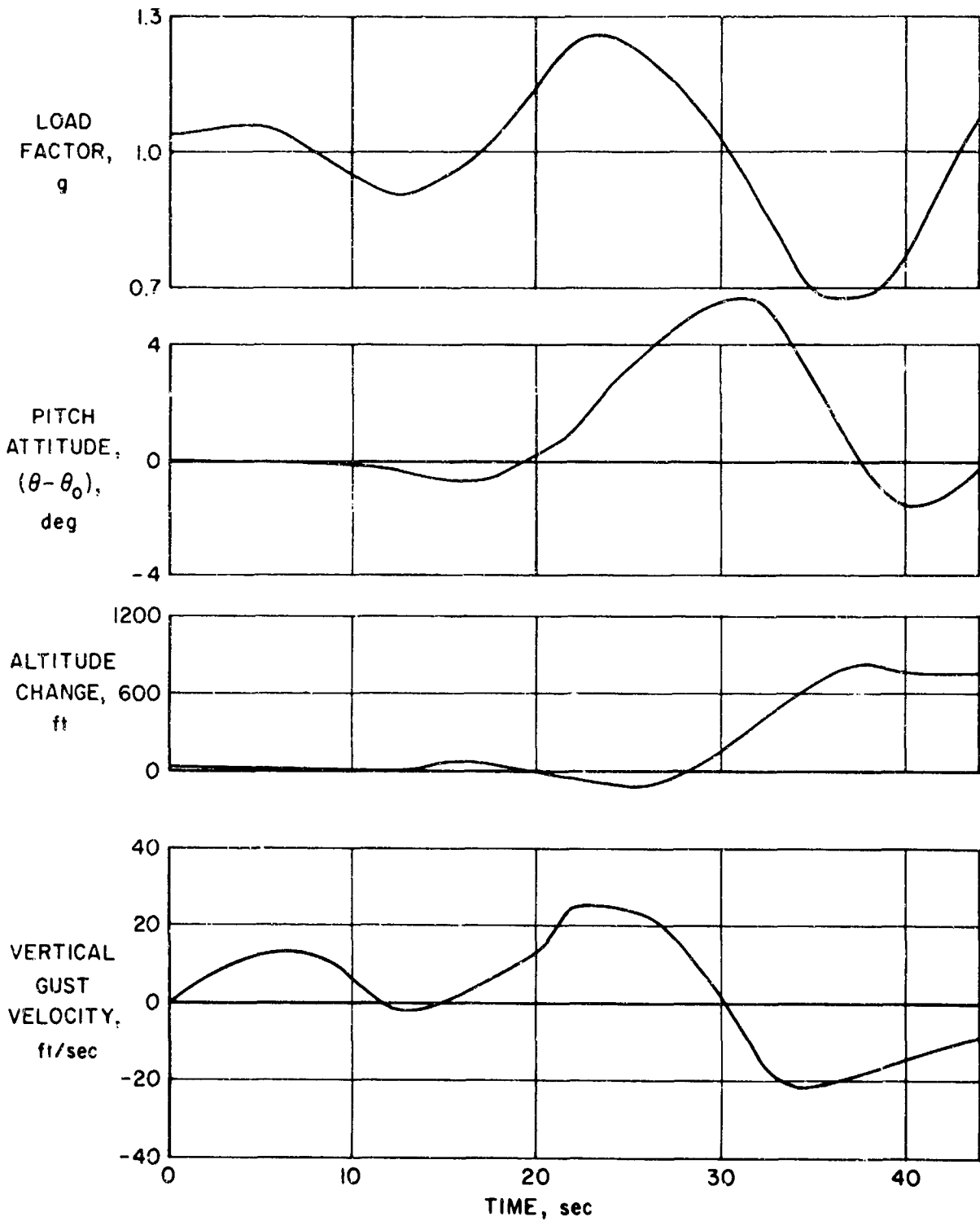


FIG. II: COMPUTED GUSTS FOR EVENT I OF FLIGHT #3